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RR LYRAE STARS IN NGC 6388 AND NGC 6441:
A NEW OOSTERHOFF GROUP?

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ABSTRACT

NGC 6388 and NGC 6441 are anomalies among Galactic globular clusters in that they cannot be readily placed into either Oosterhoff group I or Oosterhoff group II despite their significant numbers of RR Lyrae variables. The mean pulsation periods, $\langle P_{ab} \rangle$, of their RRab variables, at 0.71 d and 0.76 d, respectively, are even larger than for Oosterhoff II clusters. Moreover, Oosterhoff II clusters are very metal-poor, whereas NGC 6388 and NGC 6441 are the most metal-rich globular clusters known to contain RR Lyrae stars. The location of the NGC 6388 and NGC 6441 RRab variables in the period-amplitude diagram implies that the RR Lyrae stars in those two clusters are brighter than expected for their metallicities. Our results therefore indicate that a universal relationship may not exist between the luminosity and the metallicity of RR Lyrae variables.

Subject headings: Stars: variables: RR Lyrae stars; Galaxy: globular clusters: individual (NGC 6388, NGC 6441)

1. INTRODUCTION

Oosterhoff (1939) called attention to a dichotomy in the properties of RR Lyrae stars (RRLs) belonging to five RR Lyrae-rich globular clusters. The five clusters could be divided into what are now known as Oosterhoff groups I (Oo I) and II (Oo II) on the basis of the mean periods and relative proportions of their RRab and RRc stars (Table 1). Subsequent investigations confirmed that all Galactic globular clusters which contain significant numbers of RRLs could be assigned to either Oo I or Oo II. It also became clear that globular clusters of Oo I were more metal rich than those of Oo II (Smith 1995 and references therein). The cause of the Oosterhoff dichotomy, and its implications for the brightnesses of RRLs and the ages of globular clusters, remains a subject of debate (van Albada & Baker 1973; Sandage, Katem, & Sandage 1981; Castellani 1983; Renzini 1983; Lee, Demarque, & Zinn 1990; Sandage 1993a, 1993b; Clement & Shelton 1999).

Although RRLs more metal rich than [Fe/H] = −0.8 are known to exist in the field population of the Galaxy (Preston 1959; Layden 1994), very few RRLs have been discovered within the most metal rich globular clusters. Metal-rich clusters have stubby horizontal branches (HBs) which lie entirely or almost entirely to the red side of the instability strip. The globular clusters NGC 6388 and NGC 6441 are prominent exceptions to this rule. These are relatively metal-rich globular clusters with [Fe/H] = −0.60 and −0.53, respectively (Armandroff & Zinn 1988). Their HBs nonetheless have strong blue as well as red compo-

nents (Rich et al. 1997). Studies of NGC 6388 by Hazen & Hesser (1986) and Silbermann et al. (1994) and of NGC 6441 by Layden et al. (1999) indicated that both clusters contain significant numbers of RRLs. These studies, especially that of Layden et al., also showed that RRLs within NGC 6388 and NGC 6441 have properties different from those expected of metal-rich field RRLs. In this paper we consider new observations of RRLs in both clusters which indicate that NGC 6388 and NGC 6441 do not fit into either the Oo I or Oo II groups.

NGC 6388 and NGC 6441 are also of interest because observations obtained with the Hubble Space Telescope (Rich et al. 1997) showed that the HBs of the clusters slope upward as one goes toward the blue in a V, $B-V$ color-magnitude diagram. Theoretical simulations (Sweigart & Catelan 1998) demonstrated that this slope cannot be caused by differences in age, mass loss on the red giant branch, or differential reddening. The latter possibility was also ruled out by Layden et al. (1999). Sweigart & Catelan found that theoretical scenarios which did explain this slope also predicted a high luminosity for RRLs in NGC 6388 and NGC 6441 (see also Sweigart 1999). Testing this prediction is an additional goal of this study.

2. OOSTERHOFF CLASSIFICATION OF NGC 6388 AND NGC 6441

New CCD observations of NGC 6388 and NGC 6441 were obtained in 1998 with the 0.9-m telescope at Cerro Tololo Interamerican Observatory. These observations

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were used to approximately double the number of previously known RRLs within each cluster, and to determine periods and B, V light curves for new and previously known variables. Details of the observations are presented in Pritzl et al. (1999a, 1999b). Those papers also deal with the question of RRL membership in the two clusters. Membership for RRab stars is usually straightforward but, as Layden et al. (1999) also found, there can be occasional confusion for RRc stars. For the purposes of this paper, we include only variables for which the case for membership is strong. In particular, several possible shorter period RRc are not included in deriving the N_c/N_{RR} ratios of Table 1. The more questionable variables are dealt with fully in Pritzl et al. (1999a, 1999b).

TABLE 1
CLUSTER PROPERTIES

Cluster	Type	[Fe/H]	$\langle P_{ab} \rangle$	N_c/N_{RR}
M3	Oo I	-1.6	0.56 d	0.16
M15	Oo II	-2.2	0.64 d	0.48
NGC 6388	?	-0.6	0.71 d	0.60
NGC 6441	?	-0.5	0.76 d	0.40

Mean properties of RRLs in NGC 6388 and NGC 6441 are summarized in Table 1, together with those of RRLs in M3 and M15, typical Oo I and Oo II clusters. NGC 6388 and NGC 6441 are distinguished by the surprisingly long mean periods of their RRab stars. The distinction is emphasized in Figure 1, where NGC 6388 and NGC 6441 stand out sharply from Oo I and Oo II clusters in the $\langle P_{ab} \rangle$ versus [Fe/H] diagram. NGC 6388 and NGC 6441 are not only the most metal-rich clusters plotted in Figure 1, but also the clusters with the largest values of $\langle P_{ab} \rangle$, completely contradicting the trend seen among the other clusters.
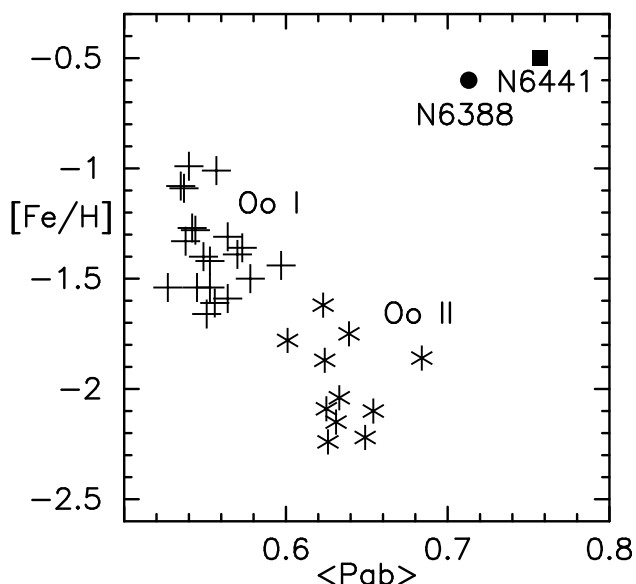

FIG. 1.—Mean period vs. [Fe/H] diagram showing the offset of NGC 6388 (circle) and NGC 6441 (square) from the Oosterhoff I (crosses) and Oosterhoff II (asterisks) globular clusters. Data for the Oosterhoff clusters are taken from Sandage (1993b).

The unusual nature of NGC 6388 and NGC 6441 is also indicated in the period-amplitude diagram plotted as Figure 2. The usual differences between the Oosterhoff groups are apparent in this figure. At constant amplitude, RRab stars in the Oo II clusters M15 (Silbermann et al. 1995; Bingham et al. 1984) and M68 (Walker 1994) are shifted toward longer periods compared to those in the Oo I cluster M3 (Carretta et al. 1998), while metal-rich field RRab stars occur at shorter periods. In contrast, NGC 6388 and NGC 6441 RRab stars have, at a given amplitude, periods as long as, and in some cases, longer than those of Oo II RRab stars. It should be noted that, in selecting comparison stars to plot in Figure 2, obvious Blazhko variables have been excluded, but no more stringent light curve criteria have been applied.
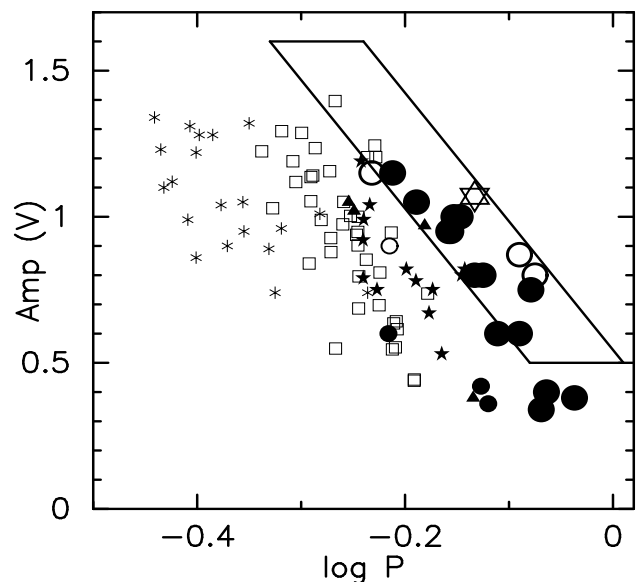

FIG. 2.—Period-amplitude diagram for the ab-type RR Lyrae variables of NGC 6388 (open circles) and NGC 6441 (filled circles) as compared to field RR Lyrae of [Fe/H] ≥ -0.8 (asterisks), V9 in 47 Tuc (six pointed star), M3 (open boxes), M15 (stars), and M68 (triangles). The smaller circles denote variables that are believed to be blended with companions or possibly to be Blazhko stars.

RRab star periods longer than 0.8 days account for 50 and 37 percent of the RRab stars in NGC 6388 and NGC 6441 respectively. Such long periods are rare but not unprecedented among other globular clusters. The globular cluster ω Centauri, unique in containing RRLs with a wide range in [Fe/H] (Butler, Dickens, & Epps 1978), also contains a significant number of very long period RRab stars. Although ω Cen is primarily an Oo II cluster, it has been suggested that it contains RRLs belonging to both Oosterhoff groups (Butler et al. 1978). However, most of its RRab stars have periods much shorter than those in NGC 6388 and NGC 6441. As another example, Wehlau (1990) found the three RRab stars in the globular cluster NGC 5897 to all have periods longer than 0.79 d. NGC 5897 is a metal-poor cluster, however, with [Fe/H] $= -1.68$ (Zinn & West 1984), and in that regard is unlike NGC 6388 and NGC 6441. With a period of 0.737 d, the RRL V9 in the metal-rich globular cluster 47 Tuc may be a closer analogue to the RRab stars in NGC 6388 and

NGC 6441 (Figure 3 of Sweigart & Catelan 1998; Carney et al. 1993).

Period histograms for NGC 6388, NGC 6441, M3, and M15 are shown in Figure 3. Like the very metal-poor Oo II clusters, NGC 6388 and NGC 6441 are relatively rich in RRc stars. On the other hand, as we have already noted, the metallicites of NGC 6388 and NGC 6441 are similar to, but even higher than, those of Oo I. Once again, NGC 6388 and NGC 6441 stand out as anomalous.

We conclude that NGC 6388 and NGC 6441 cannot be readily classified as either Oo I or Oo II from the properties of their RRLs. The long mean periods of their RRab stars, their location in the period-amplitude diagram, and the large proportions of RRc stars all support an Oo II classification (see also Clement 1999a). However, the mean RRab periods are longer than for Oo II clusters and the high metallicities of NGC 6388 and NGC 6441 stand in contradiction to the low metallicities of Oo II systems. We also note that NGC 6388 and NGC 6441 are very different from the globular clusters of the Large Magellanic Cloud, which do not fall into either Oo group (Bono, Caputo, & Stellingwerf 1994). Those clusters are metal-poor and have values of $\langle P_{ab} \rangle$ intermediate between Oo I and Oo II. We therefore suggest that NGC 6388 and NGC 6441 might represent a new Oosterhoff class.

3. THE LUMINOSITY OF THE RR LYRAE STARS

Sandage et al. (1981) noted a shift in period between RRLs in M3 and M15, measured at constant T_{eff} or constant amplitude. Using Ritter's relation, $P\sqrt{\langle \rho \rangle} = Q$, they interpreted this as evidence that the M15 RRLs were less dense and thus more luminous than those in M3. This was later generalized to a luminosity-metallicity correlation, in the sense that RRL brightness increases with decreasing [Fe/H] (Sandage 1982; Carney et al. 1992). This luminosity-metallicity correlation is generally represented by a linear equation of the form $M_V = \alpha \times$ [Fe/H] $+ \beta$, where α denotes the sensitivity of RRL luminosity to metallicity. The size of this correlation remains subject to debate, with values of α ranging from 0.3 (Sandage 1993a) to 0.13 (Fusi Pecci et al. 1996). We note, however, that there has been recognition that this linear relationship may not always apply, as, for example, in describing the relationship between metallicity and luminosity among the RR Lyrae variables in ω Cen (Butler et al. 1978; Dickens 1989; Lee 1991).

On the basis of this prior work, one would expect the locus of RRab stars in the period-amplitude diagram to shift to shorter periods with increasing [Fe/H]. Comparison of the locations in the period-amplitude diagram of RRab stars in the very metal-poor globular clusters M15 and M68 with RRab stars in M3 and with metal-rich field RRab stars (Figure 2) confirms this expectation. On the other hand, RRab stars in NGC 6388 and NGC 6441 are shifted toward longer periods than would be expected from their metallicities, indicating that they are at least as bright as RRLs in very metal-poor Oo II clusters.

Sweigart & Catelan (1998), in an effort to explain the unusual slope of the HBs of these two clusters, created three theoretical scenarios which could be tested using RRLs. Their models predict that the blue HBs of NGC 6388 and NGC 6441 should be unusually bright.

Though at the time, the data available on the RRLs of the two clusters were slight, available observations were consistent with the predictions of these models.

The data now available make the case much more strongly. The boxed area in Figure 2 represents one of the model predictions (helium-mixing scenario) of Sweigart & Catelan [1998, from their Figure 3 as translated to the period-amplitude diagram by Layden et al. (1999, cf. their Figure 9)]. The period-amplitude data are in similarly good agreement with the other scenarios of Sweigart & Catelan, all of which require that the RRLs of NGC 6388 and NGC 6441 are brighter than solar neighborhood field RRLs of comparable [Fe/H].

It has been argued that HB evolution, rather than metallicity *per se*, might be the governing factor in determining whether a cluster belongs to Oo I or Oo II (Clement & Shelton 1999; Lee & Carney 1999). Lee et al. (1990) also argued that evolution was an important element in the origin of the Oosterhoff phenomenon. Oo II clusters usually have bluer HBs than Oo I clusters, although there are exceptions such as M28 or NGC 4147 (cf. Table 1 in Castellani & Quarta 1987). According to this explanation RRLs in Oo II clusters spend most of their HB lifetimes on the blue HB (BHB) before evolving redward through the instability strip on their way back to the asymptotic-giant branch. The final crossing of the instability strip occurs at a brighter luminosity and hence longer period than for stars near the ZAHB.

NGC 6388 and NGC 6441 have predominantly red HBs with pronounced blue components. The sloping HB morphology in the color-magnitude diagrams of NGC 6388 and NGC 6441 does not indicate that the RRLs in those clusters have evolved from the BHB. Moreover, Sweigart & Catelan's (1998) models indicate that the RRLs are in the main phase of HB evolution, requiring that the HBs of the clusters are unusually bright. Thus, evolution does not appear to be the explanation for the long RRL periods in NGC 6388 and NGC 6441.

The location of the NGC 6388 and NGC 6441 RRab stars in the period-amplitude diagram leads us to conclude that RRLs in those metal-rich globular clusters are at least as bright as those in the very metal-poor Oo II clusters M15 and M68. There is thus no universal correlation between RRL luminosity and metallicity. The HB morphology of the two clusters, together with the theoretical scenarios of Sweigart & Catelan, further lead us to conclude that the bright RRLs are a consequence of bright HBs rather than evolution from the BHB.

4. DISCUSSION

The relatively metal-rich globular clusters NGC 6388 and NGC 6441 are distinct in several ways from ordinary Oo I and Oo II clusters. Nor are their RRLs similar to those of the metal-rich field population of the solar neighborhood. The location of NGC 6388 and NGC 6441 RRab stars in the period-amplitude diagram is consistent with the RRLs of the two clusters being as bright or slightly brighter than those of Oo II clusters such as M15 or M68, a result consistent with the theoretical models of Sweigart & Catelan (1998). The RRLs in NGC 6388 and NGC 6441 thus demonstrate that RRL luminosity is not always inversely correlated with metallicity.

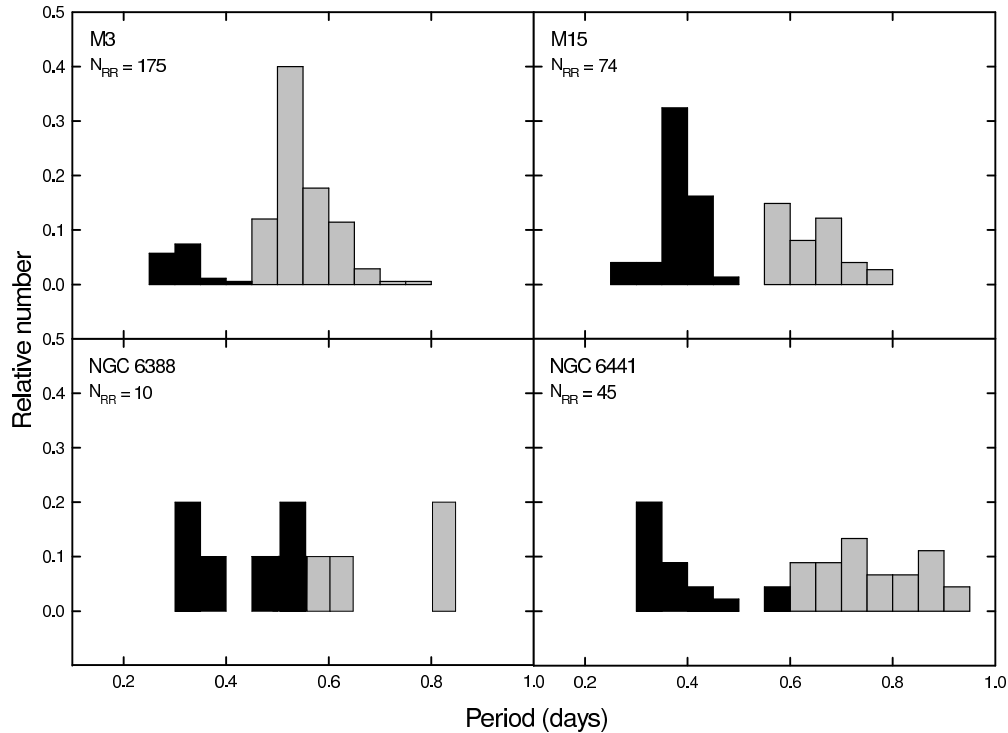Should we then regard NGC 6388 and NGC 6441 as

Fig. 3.— Period distribution histograms for the RR Lyraes of M3, M15, NGC 6388, and NGC 6441. The darker area is occupied by RRc variables. The lighter area is occupied by RRab variables. Data for M3 and M15 are taken from Clement (1999b).

sufficiently distinct from Oo I and Oo II clusters to be representatives of a third Oosterhoff group? Or should we instead regard them as an aberrant type of Oo II cluster? It is to some degree a matter of semantics, the answer depending in part upon which characteristics one regards as essential to Oosterhoff classification. It is nonetheless worth noting that NGC 6388 and NGC 6441 are alike in ways other than [Fe/H] and the properties of their RRLs. Both are among the most luminous globular clusters of the Galaxy and both have very high central densities. It remains an open but intriguing question whether those attributes play a role in producing the unusual RRL populations of the clusters.

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